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Achieving China's Intended Nationally Determined Contribution and its co-benefits: Effects of the residential sector

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ABSTRACT

In preparation for the 21st Conference of Parties (COP21) held in December 2015, the participating parties under the UN Framework Convention on Climate Change (UNFCCC) agreed to submit their own targets for national greenhouse gas emission reductions and mitigation, and adaptation actions that they intended to take under the post-2020 international framework for climate change. They were called Intended Nationally Determined Contributions (INDCs). One of the important actions by 2030 in China's INDC is to lower carbon dioxide (CO_2) emissions per unit of GDP by 60%–65% from 2005 levels. The purpose of this study is 1) to examine the efforts on China's residential sector in achieving the CO_2 reduction target stated in China's INDC, 2) to estimate the range of carbon prices and mitigation potential in the INDC targets, and 3) to analyze the co-benefits of low carbon measures to reduce emissions of major short-lived climate pollutants and air pollutants in the residential sector, such as black carbon (BC), fine particulate matter ($PM_{2.5}$), and sulfur dioxide (SO_2). To account for climate diversity and its impact on household energy service demands, our analysis divides China into 31 sub-national regions. It was found that the residential sector has significant reduction potential to succeed with "no-regret" CO_2 reduction measures. To achieve the range of China's INDC targets, households in both rural and urban China must implement more efficient technologies and marginal abatement in the range of around \$40 –\$60 US/tCO_2. Compared to the FIX scenario, CO_2, BC, $PM_{2.5}$, and SO_2 emissions from the residential sector in the whole China are respectively reduced by 38%, 21%, 16%, and 31% in 2030 in the lower boundary of the INDC targets. However, reduction rates vary across provinces due to climatic variations and economic disparities. For example, cold provinces contribute more to the total emission reductions than warm provinces, under a national carbon emission cap to achieve the INDC targets. It is also important to note that there are large co-benefits to reducing air pollutants due to low carbon measures, thus achieving the INDC targets will help improve indoor air quality in the residential sector, especially in rural areas.

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1. Introduction

Climate change and air pollution are two of the major environmental issues which China has been facing. China's economy has grown fourfold since its economic reform in 1978, and energy use has drastically increased in the process. Economic development in China relies on a coal-dominant energy mix, so energy-related GHG emissions have grown faster than energy consumption (IEA, 2010). On June 30, 2015, China submitted its "Intended Nationally Determined Contribution (INDC)" to the United Nations Framework Convention on Climate Change (UNFCCC) in preparation for the Conference of Parties 21 (COP21) held in December. China's INDC called for several low carbon measures toward 2030, including a reduction of carbon dioxide emissions per unit of GDP of around 60%–65% compared to 2005 levels. Air pollution, meanwhile, has drawn widespread attention in China, where many major cities are plagued by thick smog and high levels of fine particulate matter ($PM_{2.5}$). Since the smog catastrophe of 2013, the Chinese government has made concerted efforts to improve air quality in urban areas. In September 2013, the State Council of China issued an "Air Pollution Control Action Plan" (State Council of China, 2013) that sets three principal air pollution improvement targets for 2017.

Air pollution and climate change are two serious issues that China is currently facing and have drawn attention in the scientific

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community. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) addressed both climate change mitigation and air pollution issues, such as human risk exposure to PM_{10} pollution in 3200 cities worldwide (IPCC, 2014). The report also pointed out that on a global scale, climate policy has the co-benefit of reducing emissions of air pollutants. It also quantitatively evaluated the impact of stringent climate policy on BC and SO_2 emissions. Hanaoka et al. (2014) analyzed the reduction potential of multiple air pollutants from taking low carbon measures to achieve the two-degree global temperature change limit target in 32 world regions. However, these studies have explored the co-benefits of reduced greenhouse gases and air pollutants with a primary focus on world regions in the long-term but not at a Chinese regional scale. Some studies, such as Sun et al. (2016), Gambhir et al. (2015), and Yuan et al. (2016) have focused on China, estimating CO_2 emissions in China's industrial, residential, and road transport sectors at a regional scale with an emphasis on the effects on climate change. Kang et al. (2016) examined the Kuznets curve of CO_2 in China using spatial panel data. From the viewpoint of air pollution, Gao et al. (2016), Hu et al. (2015), and Zhang et al. (2015a) extensively discussed air pollution control measures for SO_2, NO_x, and fine particulate emissions in China. However, these previous studies have tended to treat climate change and air pollution as independent issues in China despite the known contributions of climate change mitigation policies to improving air quality. In this study, we first examine the efforts on the residential sector in China's urban and rural provinces in achieving the CO_2 reduction targets stated in China's INDC. We then evaluate the co-benefits of reduced BC, $PM_{2.5}$, and SO_2 emissions as a result of achieving China's INDC to elucidate the contributions to China's air quality improvement target in urban areas.

Several recent studies (Eom et al., 2012; Shi et al., 2016; Zhang et al., 2015b; Peng et al., 2015) have examined building energy efficiency throughout all of China, without considering regional disparities. Some considered differences across regions but focused solely on the climate or economic conditions. For instance, Zhao et al. (2012) surveyed household energy consumption in four kinds of Chinese regions (provincial capital, medium-sized city, county town, and rural area) and examined the impact of the population scale and per capita income on energy consumption per household. Their method, however, resulted in the same per household energy consumption both in cold and warm areas with the same per capita income (e.g., Beijing and Shanghai). This result leads to a divergence from the present situation, because cold areas have much higher energy consumption due to the use of space heating services in the winter. Yu et al. (2014) proposed a regional approach of estimating building energy demand by dividing China into four climatic areas. However, they based the study on climatic zoning only and ignored economic disparities. The sub-national regions of China vary widely in both climate and levels of economic development (The Economist, 2014). Climatic and economic disparities between regions lead to differences in demand for energy services. Thus, in our quantitative analysis of greenhouse and air pollutant gas emissions, we stress the importance of regional analysis in considering diversity at the sub-national level and in considering climate characteristics among different regions.

This study examines the efforts of the residential sector when achieving the CO_2 reduction targets stated in China's INDC, and analyses the co-benefits from low carbon measures to reduce emissions of the major short-lived climate pollutants and air pollutants in the residential sector such as BC, $PM_{2.5}$ and SO_2. We begin by projecting urban and rural residential energy service demands in 31 Chinese province-level divisions in consideration of their climate characteristics. Next, we assess energy efficient technologies by using the AIM (Asia-Pacific Integrated Model)/Enduse model, which is a bottom-up technology optimization model to evaluate multiple-gas emissions and reduction potentials. This study addresses the residential building sector and offers suggestions for achieving China's INDC in the residential sector by 2030. This study can contribute to previous studies in the following three aspects. First, we not only concentrate on CO_2 emission reduction but also consider the co-benefits of reducing air-pollutants. Second, the impact of efficient technologies on CO_2 emission reduction and the co-benefits of reducing air-pollutants are analyzed on a regional basis with full consideration of both climate and economic disparities. Finally, China's INDC is a newly proposed low carbon development plan, and this study provides a timely analysis on achievability of INDC.

The remainder of this paper is structured into Sections 2, 3, and 4. Section 2 describes the methodology for evaluating multiple-gas emissions and reduction potentials. Section 3 presents the results of the estimated multiple-gas mitigations at both national and regional levels and an in-depth discussion on the carbon price in China's INDC. Section 4 summarizes key conclusions and issues for future research.

2. Methodology

2.1. Sub-national analyses and socioeconomic indicators

Mainland China has 31 provincial-level regions[1]. The climate in China varies widely, ranging from tropical regions in the south to subarctic areas in the north. Differences in latitude and longitude produce sharp variations in precipitation and temperature. The country can be divided into five climate zones for modelling environment conditions: severe cold; cold; hot summer/cold winter; temperate; and hot summer/warm winter. In addition to climate characteristics, varying levels of economic development also have a huge impact on household energy service demands. China's climactic divide separates the country into northern (central heating) and southern (no central heating) regions, while its economic divide separates it into eastern and western regions. In this research we cover the whole of China but analyze the data at a division scale on the provincial level. We consider both economic and climate conditions in our estimations of energy service demands.

GDP and population growth are principal drivers of the future energy demands. In this research we used the Shared Socioeconomic Pathways (SSPs), a set of qualitative and quantitative narratives that describe future socioeconomic conditions to identify socioeconomic indicators such as population, GDP, and urban population share. The SSPs were recently developed by the scientific community to enable the exploration of factors that are important for the assessment of future greenhouse gas emissions and mitigation and adaptation activities. The SSP database (IIASA, 2012) provides five narratives, each describing a different socioeconomic scenario of the future based on various challenges (Van Vuuren et al., 2012). A sensitivity analysis we conducted earlier on three SSPs showed a rather small differential of residential energy service demand in China up to 2050 from one SSP to another (Xing et al., 2015a). In this study, therefore, we use SSP2 (Middle of the road), a narrative that describes a “business-as-usual” world and expects common trends in recent decades to continue, with some progress toward achieving development goals. The original SSP database only provides quantification data at the country level. To conduct our analysis at the provincial level, we disaggregate the original national value to provincial values (Xing et al., 2015a). Fig. 1 illustrates the socioeconomic indicators of 31 sub-national Chinese regions in 2010 and 2030.

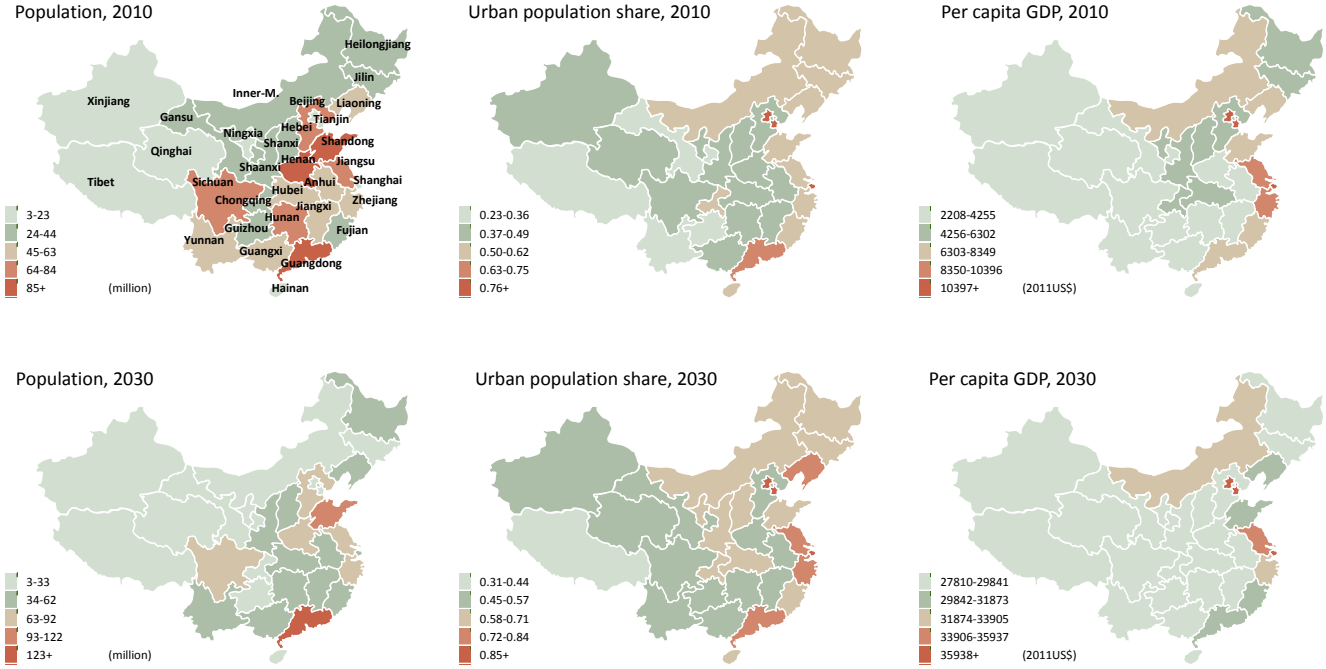

Fig. 1. Socioeconomic indicators of 31 sub-national Chinese regions.

2.2. Future energy service demands

In previous studies we estimated future energy service demands in the Chinese urban and rural[2] residential areas using a macro-model (Xing and Ikaga, 2013; Xing et al., 2015b). Specifically, we estimated energy service demands using the decomposition analysis method. We calculated the service demands of heating, cooling, hot water use, and electronics from energy usage settings (electronics working hours, frequency of showers/face-washing, etc.) and socioeconomic indicators (per capita GDP, population, etc.). Income levels in urban and rural areas were also considered in the estimations of income-induced service demands in the future (Xing et al., 2015b). We estimated service demand on a regional basis in both urban and rural residential sectors. Fig. 2 shows the aggregated national energy service demands drawn from the results of those studies. Energy service demands are around 2.5 times larger in urban areas than in rural areas, and as income rises, residential service demands are expected to more than triple by 2030 in both urban and rural areas compared to the 2010 levels. Characteristics of shares in sub-sectoral energy service demands are different from urban and rural areas.

2.3. Scenario settings

To discuss the effects of mitigation measures compared with non-mitigation policies and evaluate the growth of multiple-gas emissions and reduction potentials, we prepared three scenarios: the Fix (FIX), No carbon policy (REF), and Intended Nationally Determined Contribution (INDC) scenarios. In the FIX scenario, the technologies can be regarded to be frozen; the future technology level and its share remains as the same level as at the base year (2010) and no energy efficient technologies are implemented. Thus, FIX is designed to offer a picture of how multiple-gas emissions will increase without the intervention of any efficient technology, and it describes an aspect of emission increase or decrease when the energy service demand increases or decreases in the future. In the REF scenario, efficient technologies stored in technology databases can be selected in the future market without any carbon tax or carbon policy. Traditional technologies compete with efficient technologies over cost effectiveness, but no carbon pricing is imposed. REF describes a picture of an autonomous energy efficiency improvement process when efficient technologies are selected for minimizing the total system cost without additional carbon policy under several constraints, such as satisfaction of service demands and availability of energy supplies. It is important to note that two constraints take effect, however, during the technology selection process in the REF scenario. The first constraint addresses the future share of non-commercial energy in the rural residential sector. Non-commercial energy sources, such as firewood or straw, currently account for over 80% of the rural residential energy demand (Evans et al., 2014). Most of the non-commercial energy is collected by household members and has no commercial value, which makes it preferable for selection under the framework of minimizing total system costs in the model. However, the burning of these non-commercial fuels in indoor environments can cause serious air pollution problems. To dispel this risk in the REF scenario, from the viewpoint of air pollutant policy, we neither encourage the use of non-commercial energy nor set the share of non-commercial energy beyond the current (2010) level. The second constraint addresses the future share of renewable energies. Renewable energy technologies are sustainable alternatives for the future, but there are limits to the extent to which they can be exploited in the near-term up to 2030. Thus, exogenous constraints are added for renewables in the model simulations because sudden increases in the capacity of Chinese renewable energy are unforeseeable under the current circumstances. In the REF scenario, the shares of these renewables never surpass the level reported in the IEA's 450 scenario (IEA, 2015a).

The REF scenario sets no emissions cap or emissions tax and only accounts for the effects of no-regret mitigation options. In contrast, the INDC scenario sets the constraint in the unit of residential CO_2 emissions per GDP in 2030 to meet the lower boundary of the INDC targets at 60% compared to 2005 levels. This emissions cap refers to one of the actions in China's INDC (NDRC, 2015).

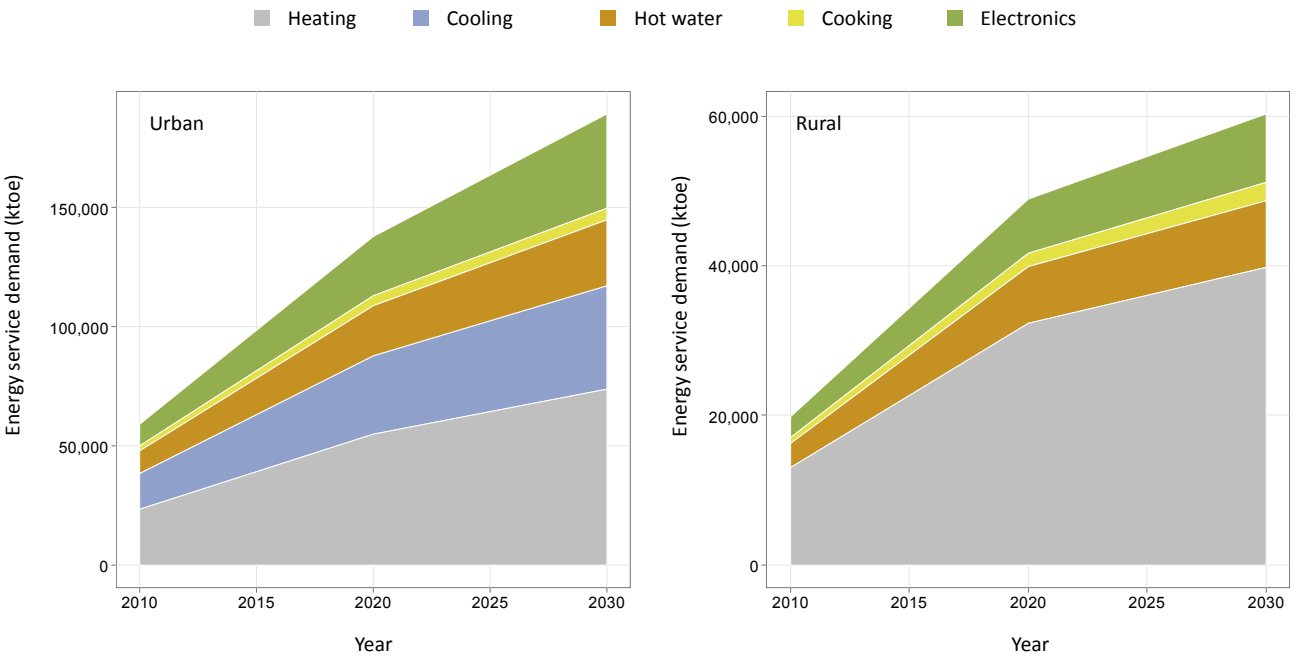

Fig. 2. Energy service demands in China's urban and rural residential sectors.

According to the 2005 data from the IEA statistics, the residential sector contributed 5% of the total CO_2 emissions (IEA, 2015b; IEA, 2015c), and the CO_2 emission intensity stood at 0.8 kg/US$ (World Bank, 2017), which puts the residential CO_2 emission intensity at 0.04 kg/US$. Several studies show that the share of residential CO_2 emissions in China has maintained a stable level since 2000 and will not change significantly in the next few decades (LBNL, 2011; Liu, 2015). The INDC scenario in this study therefore sets the residential CO_2 emission share at the same level as 2005 while setting the CO_2 emission intensity at 0.016 kgCO2/US$, a level that will enable China to realize the 60% reduction target in the residential sector proposed in its INDC. The deployment rates of efficient technologies must exceed the rates in the REF scenario to meet this emissions cap and satisfy the INDC scenario. The same constraints on non-commercial and renewable energies in the REF scenario also apply to the INDC scenario. Table 1 summarizes the definitions of the three scenarios.

2.4. Emission factor settings

The present emission factors for coal, oil products, natural gas, and biofuels are considered based on various inventory guidelines (EEA, 2009; EEA, 2013; IPCC, 2006) and peer-reviewed papers (Klimont et al., 2009; Zhao et al., 2011; Qin et al., 2012; Streets et al., 2004; Cao et al., 2006; Zhang et al., 2009; Wei et al., 2008; IIASA, 2008). We set the future emission factors based on the storylines of the SSPs. Each SSP describes a different socioeconomic scenario of the future. Five socioeconomic pathways to mitigation and adaption are translated into five narratives based on various challenges (Van Vuuren et al., 2012). In SSP3, for example, we assume that no or fewer air pollution control policies are introduced, so that future emission factors for the study are set at the same level as the base year 2010. In SSP2, we assume that the current legislative policies towards air pollution and future emissions trends will stay in line with the historical trend. Thus, the future emission factors in this study are set to gradually or slightly decrease in pace with the historical policy implementation towards air pollutants seen in the emission inventory by REAS (Regional Emission Inventory in Asia). In this study we use emission factors based on the storylines of the SSP2, the “Middle of the road” storyline that describes the world as “business-as-usual” and expects common trends in recent decades to continue, with some progress toward achieving development goals. The assumed emission factors for BC, $PM_{2.5}$, and SO_2 in this study all decreased through the past decades. To “continue the past trend,” this study also sets the emission factors for the three gases at progressively lower levels in the future.

Both direct and indirect gas emissions are considered as emissions from the residential sector in this study. Under our definition, indirect emissions are attributed to residential electricity and heat consumption. The emission factors for electricity and heat are calculated by Equation (1). Secondary energy production from each primary energy source is taken from the IEA's projections (IEA,

Table 1
Scenario overview.

Scenario	Description
Fix (FIX)	The level of future technology efficiency and diffusion ratio are fixed at 2010 levels.
Reference (REF)	Efficient technologies autonomously penetrate in future markets without considering any carbon policy.
INDC	Efficient technologies penetrate in future markets to achieve the emission levels determined by China's INDC.

Note 1 In both REF and INDC, the share of non-commercial energy does not surpass 2010 levels.
Note 2 In both REF and INDC, the maximum share of renewable energy does not surpass the level reported in the IEA's 450 scenario.
Note 3 Emission levels in China's INDC: The CO_2 emission intensity of the residential sector is set as 0.016 $kgCO_2$/US$, which is equivalent to the lower boundary (60% reduction compared to 2005 levels) of the INDC targets.

2015a). According to the IEA's Current Policy (CP) Scenario, energy efficiency in China's power sector can be improved in the future. In the IEA's CP scenario, electricity production from coal decreases from 77% in 2010 to 62% in 2030. Meanwhile, the primary energy share of gas and nuclear in the power sector increases by a wide margin over the same period. Fig. 3 shows emission factor estimates of the four gases covered for electricity and heat in the study. Air-pollution-removal devices have been gradually adopted in the electricity and heat generation sectors over the past decades (REAS, 2016). As a consequence, the future emission factors mostly tend to decrease in line with the historical trend in the electricity and heat generation sectors.

$$EF_{t,i} = \frac{\sum_j P_{t,i,j} \times EF_j}{\sum_j P_{t,i,j}} \quad (1)$$

where

t is the year
i is secondary energy (electricity and heat)
j is primary energy
$EF_{t,i}$ is the emission factor
$P_{t,i,j}$ is the secondary energy production from each primary energy

2.5. Technology selection framework

The AIM/Enduse model is a bottom-up optimization model designed to analyze mitigation measures and estimate multiple-gas mitigation potentials (Kainuma et al., 2003; Hanaoka et al., 2015). The country scale AIM/Enduse database has been developed over the past 20 years by researchers from various countries. More recently, the AIM/Enduse study also focuses on regional diversities. We base the present study on the newly developed regional model, AIM/Enduse [China].

The AIM/Enduse model consists of three main databases: energy and emissions factors, technologies, and socio-economic scenarios. The energy and emissions factors database consists of information such as emission factors, energy prices for each kind of energy, and emission constraints. The technology database consists of information on device efficiency, initial and operating costs, product lifetime, and so on. The socio-economic scenario database consists of information such as energy service demand, population, and GDP. The model first determines combinations of technologies with the least total system cost that can satisfy future service demand, based on the service demand and technology database. Next, the energy and GHG (greenhouse gas) and air pollutant emissions caused by the determined technology combination are estimated using information from the technology database and energy and emissions factors database. During the technology selection process, estimated service demands are satisfied by existing technologies in the base year (2010), and later satisfied by both existing and efficient technologies using the AIM/Enduse model in the target year (2030).

For each household device, an existing technology (EXT) was assigned a low efficiency, one or more alternative technologies (NEW) were assigned a higher efficiency, and the best available technology (BAT) is assumed to be the most efficient technology, based on the realistic and currently existing technologies in the mitigation option database. Table 2 gives an example of the three technology levels in this study. The model selects technology combinations for each region based on the least total system cost.

Table 2
Example of device efficiencies/COPs (supplied/consumed) of the three technology levels.

Device	Efficiency (or COP for air conditioner)		
	EXT	NEW	BAT
Urban household			
Gas cooking range	0.53	–	0.56
Heating air-conditioner (grid electricity)	2.80	3.20	6.34
Rural household			
Firewood cooking range	0.53	–	–
Heating stove (coal)	0.39	–	0.53

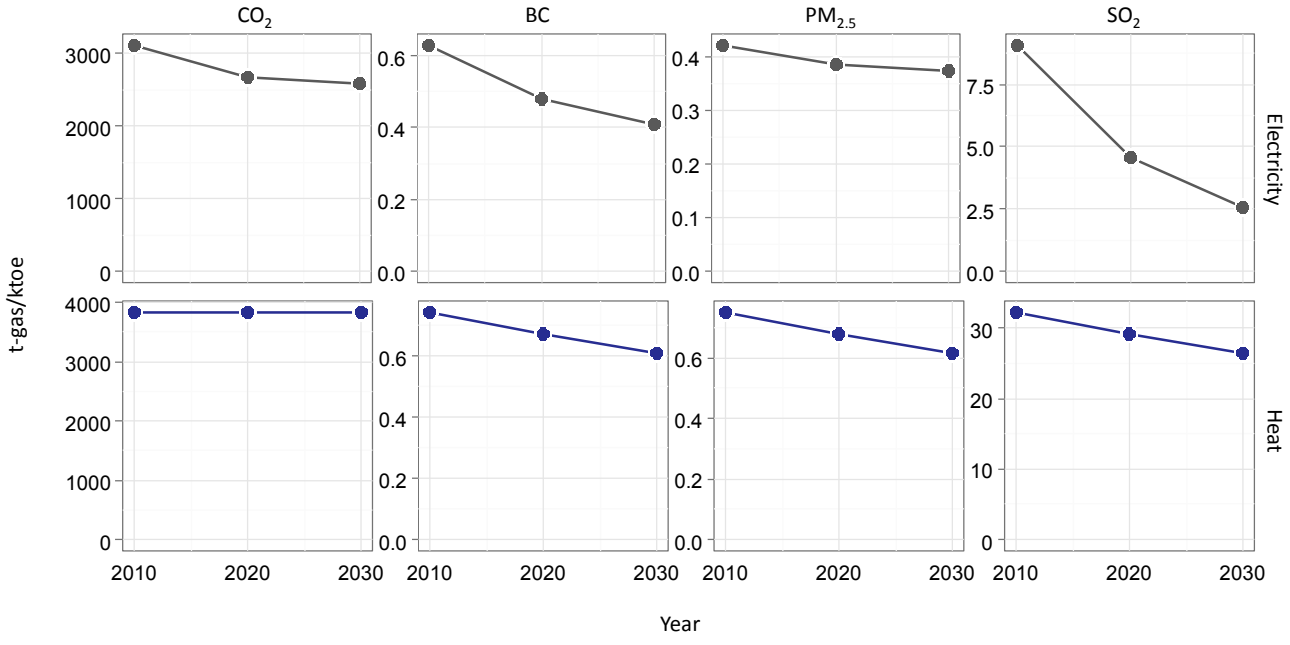

Fig. 3. Emission factors for electricity and heat.

Urban households and rural households have very different energy structures. Commercial energy is widely used in urban households (e.g., city gas), while traditional biomass occupies more than 80% of the total energy consumption by rural households (Evans et al., 2014). To accommodate the marked differences in lifestyles and existing electronic types between urban and rural households, we prepared separate technology datasets for urban and rural households based on specific conditions. The complete dataset of efficient technology consists of 77 devices for urban households and 83 devices for rural households (Xing et al., 2015a, 2015b).

2.6. Energy and device cost settings

The present study divides China into 31 provincial-level regions and considers abatement costs in the residential sector in each provincial region. Our research also uses the AIM/Enduse [ACC] tool (Hanaoka et al., 2015) to project abatement potentials and costs of CO_2 emissions per device from China's residential buildings. There are three important parameters in estimating the abatement cost per device: energy price, device cost, and carbon price.

Energy prices of electricity, diesel, natural gas and coal in the base year (2010) are taken from the IEA (2010). Commercial biomass has recently been introduced into the Chinese market, and is a type of wood biomass that has lower emission factors of air pollutants compared to non-commercial biomass. In this study, commercial biomass is considered an environmentally friendly energy source for rural households. However, the promotion of commercial biomass is still at the experimental stage and its price is not included in IEA's statistics. The price of commercial biomass in the base year therefore takes reference from the Chinese energy supply market (China-nengyuan, 2017). Energy prices are expected to escalate in the future. We use the same increase rates as IEA's assumptions for international energy import prices (IEA, 2015a; IEA, 2015c). Table 3 shows the settings of current and future prices of five energy sources in this study. Device costs are average values of widely-used devices (NIES, 2012) that consider purchasing power parity (World Bank, 2016).

2.7. Carbon price estimations

As explained in Section 2.3, there is no carbon tax setting in the FIX and REF scenarios because these scenarios are considered without any carbon policy. The INDC scenario does not include any direct carbon tax setting, but it does have an emissions cap to meet the reduction target in INDC. Thus, we can calculate a marginal abatement cost when achieving the INDC target, which is a shadow price under the linear optimization framework. Therefore, in this study, we first used the AIM/Enduse model to conduct a sensitivity analysis on the range of carbon prices under several emission constraints and estimated the range of carbon prices to realize China's INDC targets (60%–65% per GDP CO_2 emission reduction compared to 2005 levels). We then use the AIM/Enduse [ACC] tool to analyze device-by-device technological mitigation potentials and abatement costs within a range of carbon prices to meet the INDC targets.

Table 3
Energy prices. (Unit: $1,000US/ktoe).

Energy	2010	2020	2030	2040	2050
Coal	140.43	168.51	202.22	232.18	263.07
Electricity	894.95	1008.15	1416.01	1627.44	1887.97
Diesel	668.09	825.94	1057.07	1239.35	1433.84
Natural gas	368.27	579.95	684.58	860.57	1018.73
Biomass	422.43	506.91	608.29	698.41	791.35

AIM/Enduse is a recursive dynamic optimization model that simulates scenarios simultaneously from the base year through the target year. On the other hand, AIM/Enduse [ACC] is a static optimization tool to estimate reduction potentials and mitigation costs per device and describe abatement cost curves (ACC) in the target year of the results of detailed technology selections. In conducting the estimation, FIX is set as the baseline, and the future share and energy efficiency of standard technologies are fixed at the same level as the base year. Therefore, reduction potentials are defined as "reduction amounts which are estimated by comparing the effect of introducing new mitigation technologies in the target year as compared to the effect of standard technologies fixed at the same level as the base year." Mitigation costs are defined as the additional costs, including capital and operational costs, which are required for introducing new mitigation measures.

Abatement potentials and cost curves in the ACC tool in target year (t), target sector (i) and service type (j) are described as follows:

1) Calculate CO_2 emission reduction of an energy device l, $\Delta\widehat{Q}_{l,i}^{t}$; additional cost of an energy device l, $\Delta\widehat{C}_{l,i}^{t}$; and maximum potential of stock of an energy device l, $\Delta S_{l,i}^{\max,t}$ in time period (year) t. $\Delta S_{l,i}^{\max,t}$ represents the differences between the respective values in the time period t and in the base year t_0.
2) Plot the abatement cost of unit reduction $\Delta\widehat{C}_{l,i}^{t}/\Delta\widehat{Q}_{l,i}^{t}$, along the y-axis, and CO_2 emission reduction of an energy device l, $\Delta\widehat{Q}_{l,i}^{t}$ along the x-axis in order of ascending abatement cost of unit reduction, where region or sector is (i), service type (j), Energy type (k), Energy device (l), Gas type (m), Time period (year) (t), Base year (0), and Quantity per unit (^).

3. Results and discussion

3.1. Emissions in the Chinese residential sector

Fig. 4 shows the aggregated estimation results for CO_2, BC, $PM_{2.5}$, and SO_2 emissions in China's urban and rural residential sectors. In urban areas, CO_2, BC, $PM_{2.5}$, and SO_2 emissions respectively increase to 342%, 289%, 327%, and 256% of 2010 levels by 2030 in the FIX scenario, which shows the effects of future service demand increase. When the autonomous improvement of efficient technologies is considered in the REF scenario, CO_2, BC, and $PM_{2.5}$ emissions are expected to respectively drop by 24%, 13%, and 73% compared to the FIX levels in 2030. The significant co-benefits of $PM_{2.5}$ reduction in urban areas are estimated even in the REF scenario, due to the instalment of efficient heating devices. Thus, it is important to note that it can contribute to the enforcement of China's "Air Pollution Control Action Plan" (State Council of China, 2013). SO_2 emissions are the only exception; they increase by 10% by 2030 in the REF scenario. SO_2 emissions from urban households are mainly caused by central heating in the northern cold areas, and the share of central heating in the northern cold areas is higher in the REF scenario than in the FIX scenario. The REF scenario selects central heating rather than individual coal stoves to achieve a lower CO_2 emissions because central heating services are more cost-effective than individual coal stoves under a no-carbon-pricing condition. Thus, the share of central heating in the REF scenario is more than that of the FIX scenario. Considering that central heating has a higher SO_2 emission factor than individual coal stoves, SO_2 emissions from the increasing share of heat generation pushes total SO_2 emissions higher. With a carbon cap applied in the INDC scenario, CO_2, BC, $PM_{2.5}$, and SO_2 emissions show further reductions. In urban areas, all four gas emissions are expected to respectively drop by 32%, 34%, 74%, and 24% compared to the FIX level in 2030.

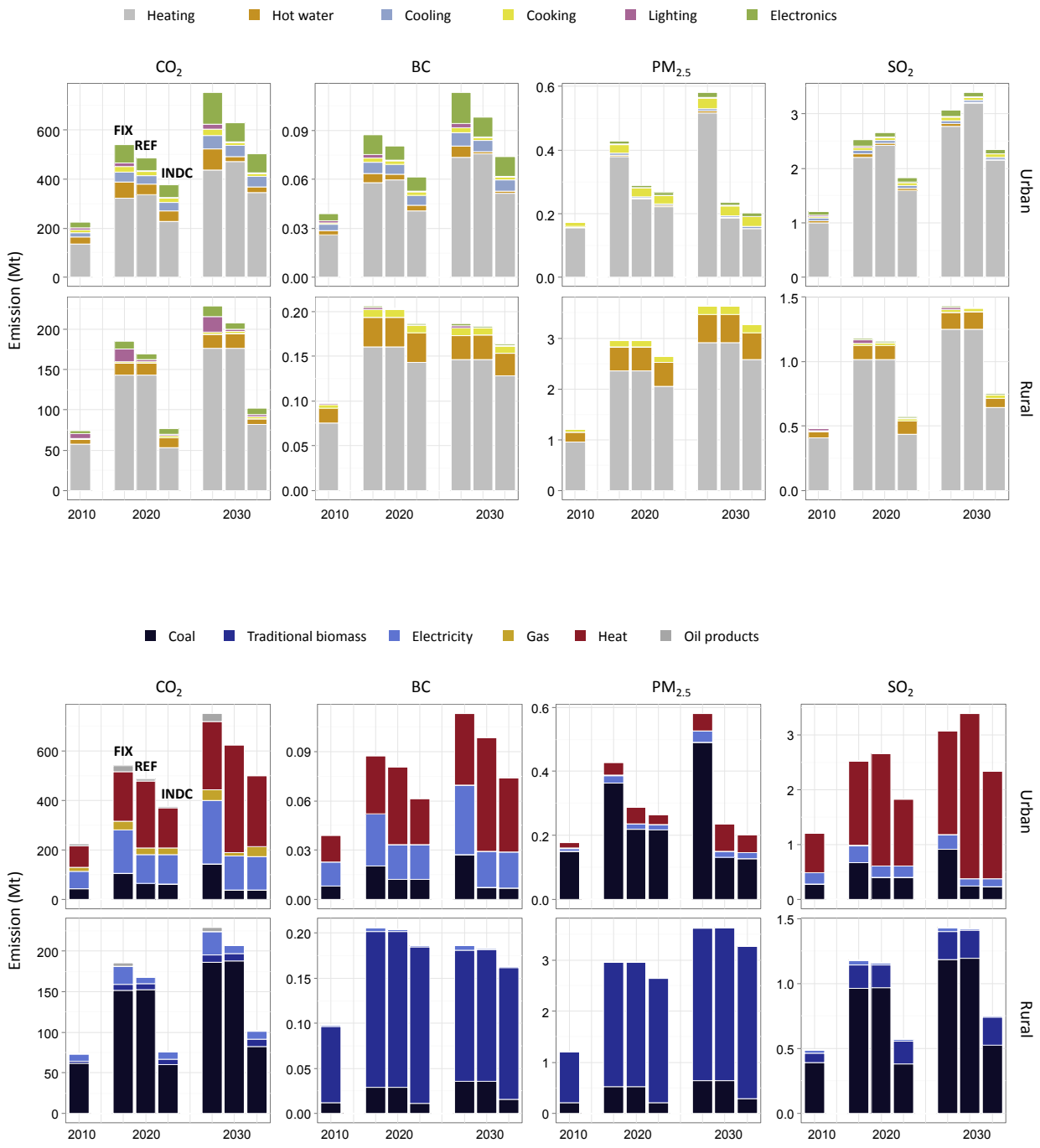

Fig. 4. Emissions of CO_2, BC, and $PM_{2.5}$ from China's residential sector.

In rural areas, CO_2, BC, $PM_{2.5}$ and SO_2 emissions in the FIX scenario respectively increase to 312%, 190%, 301%, and 294% of the 2010 levels by 2030. In the REF scenario, CO_2, BC, $PM_{2.5}$ and SO_2 emissions in 2030 are expected to respectively drop by 20%, 1%, 1%, and 1% compared to the FIX level. No-regret CO_2 reduction potential in rural households is mainly contributed to by efficient household electronics, which indicates that promoting high efficiency electronics is crucial to reducing CO_2 emissions in rural areas. The co-benefited reduction rates of BC, $PM_{2.5}$ and SO_2 are smaller than 1% in rural areas in the REF scenario because non-commercial energy sources, such as firewood or straw, currently account for over 80% of the rural residential energy demand, and its share will not change between the FIX and REF scenarios. Non-commercial biomass energy is considered to be carbon-neutral but its air pollutant emission factors such as BC, $PM_{2.5}$ and SO_2 are large, thus the share of non-commercial biomass will have a great effect on BC, $PM_{2.5}$, and SO_2 emission profiles in rural areas. In the INDC scenario, the reduction rates for CO_2, BC, $PM_{2.5}$, and SO_2 in 2030 respectively rise to 51%, 12%, 9%, and 48% compared to the FIX levels. The emission reduction potentials for BC and $PM_{2.5}$ in rural areas are quite small relative to those in urban areas. As most of the BC and $PM_{2.5}$ emissions from rural households are produced by non-commercial traditional biomass, replacing them with electricity or low-carbon-content fuels would be difficult to accomplish from a cost-optimization perspective, when achieving the level of the lower boundary of the range of INDC targets. Both energy service

demand and CO_2 emissions are lower in rural areas. However, it is important to note that BC and $PM_{2.5}$ emissions are higher in rural than in urban areas, which points to the high reliance on non-commercial traditional biomass for rural household energy, along with the detrimental effects of biomass for air quality and the health of rural residents. Thus, it is important to consider policies that encourage an energy source shift from traditional biomass to electricity or low-carbon-content fuels from the viewpoint of reducing indoor air pollution in rural areas.

3.2. Regional emissions profiles

To achieve the lower boundary of the INDC reduction targets on a national scale, each province bears a different reduction burden due to different characteristics of the major emission sources and their abatement costs across regions. Fig. 5 shows the reduction rates in the INDC scenario compared to the FIX scenario (i.e. (FIX-INDC)/FIX) of 31 sub-national regions in 2030 and their correlations with two major socio-economic indicators: per capita GDP and heating degree day 18 (HDD18). No correlation between the CO_2 reduction rate and per capita GDP appears in the regression analysis. Although Fig. 2 suggests that service demand level is higher in urban areas where the economic level is also higher, it is rash to conclude that the higher economic level will lead to greater CO_2 reduction potential. Meanwhile, we do find a negative correlation between HDD18 and the CO_2 reduction rate, the more CO_2 reduction rate rises, the more HDD18 falls, which means that warm regions contribute more to achieving the national INDC reduction target. The lack of any correlations beyond that observed between the climate indicator (HDD18) and CO_2 reduction rate suggests that residential CO_2 emissions in China are mainly influenced by demand for heating services. The major energy carrier of heating services in present-day China is coal. Replacing coal with other sustainable energy sources in the future could contribute significantly to a reduction in CO_2 emissions.

Fig. 6 shows the range of the residential multi-gas emission levels across the 31 sub-national regions in the target year 2030. The emission level of each gas in the FIX scenario in 2030 is assigned a value of 1 and compared with the emission levels in the other two scenarios in the same year. In the REF scenario (i.e. 2030REF), efficient technologies at no-regret costs are introduced into the market without any exogenous carbon policy, such as an emissions cap or emissions tax, which leads to drops in emissions of CO_2, BC, and $PM_{2.5}$ and an increase of SO_2 across all provinces. In the INDC scenario (i.e. 2030 INDC), the emissions cap restricts emission levels and more efficient technologies are promoted in the market to meet the emissions reduction goal. In the least cost optimization setting, the AIM/Enduse model selects mitigation options tailored to the conditions of the 31 regions to meet with the INDC'S lower boundary at a 60% CO_2 intensity reduction goal compared to the 2005 level at the country level. Taking the 2030 FIX emissions level as 1, CO_2 emission levels in 31 Chinese regions range from 0.43 to 0.77 in the INDC scenario by 2030. When CO_2 emission constraints are introduced in INDC, Hainan province has the largest reduction potential (0.43 compared to the 2030 FIX level) and the Tibet Autonomous Region has the lowest reduction potential (0.77 compared to the 2030 FIX level). One caveat is that there is a possibility of emission rebound – "facing a more affordable energy efficient resource, the economic actors might be more prone to use it and cause an increasing energy consumption" (Khazzoom, 1980). Empirical studies pointed out that such rebound effect led to a slow down energy efficiency progress in European countries (Copiello, 2017). However, in China it is hard to quantify the rebound effect due to lack of reliable data. Therefore this study does not consider its rebound effect in the REF and the INDC scenarios. Still, it is worth to point out the emission reduction in the REF and the INDC scenarios result from absolute energy savings (assuming positive behavioural savings from energy users).

Fig. 7 shows the estimated emissions of four gases in two representative regions from the north and south, with and without central heating services. In the cold region (Beijing) with central heating services provided during winter, gas emissions from urban households are mainly produced by electricity and heat. In the warm region (Shanghai) without central heating services, gas emissions from urban households are mainly produced by electricity. Consequently, the CO_2 emission reduction potential in Beijing is mainly contributed to by efficient heating devices (central heating) while in Shanghai the reduction potential is mainly contributed to by efficient electric devices. In rural households, gas emissions are mainly produced by coal and traditional biomass, which are the same in both cold and warm regions. Regions with hot summer and cold winter climates, such

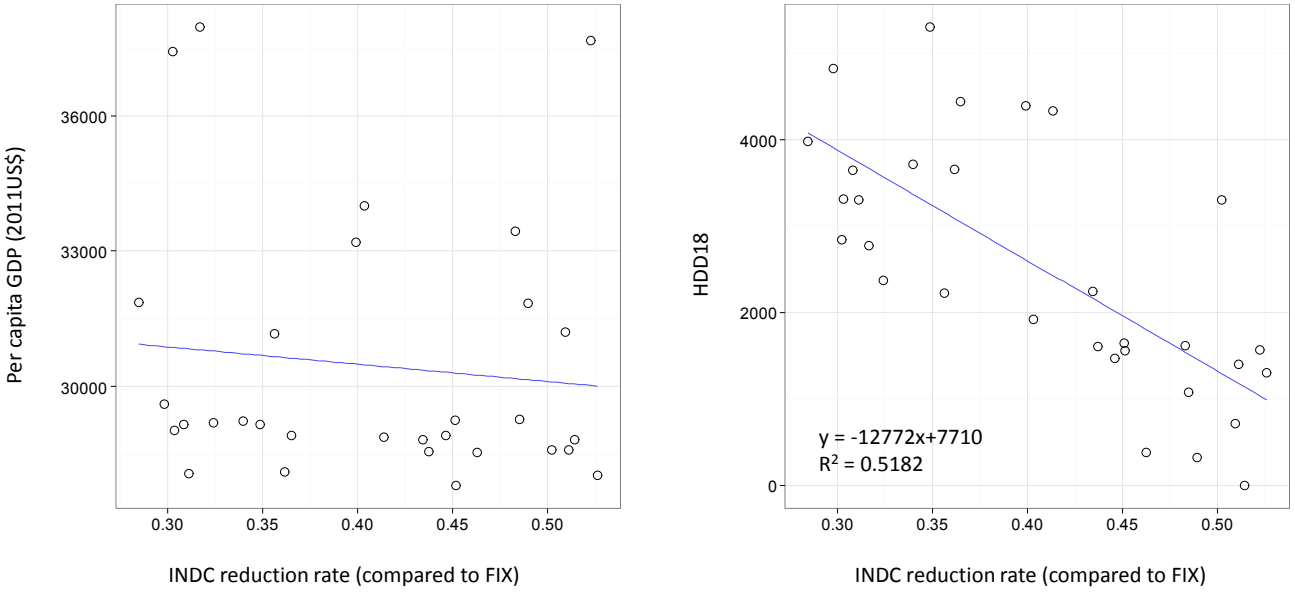

Fig. 5. Correlations between per capita GDP, HDD18, and the CO_2 reduction rate.

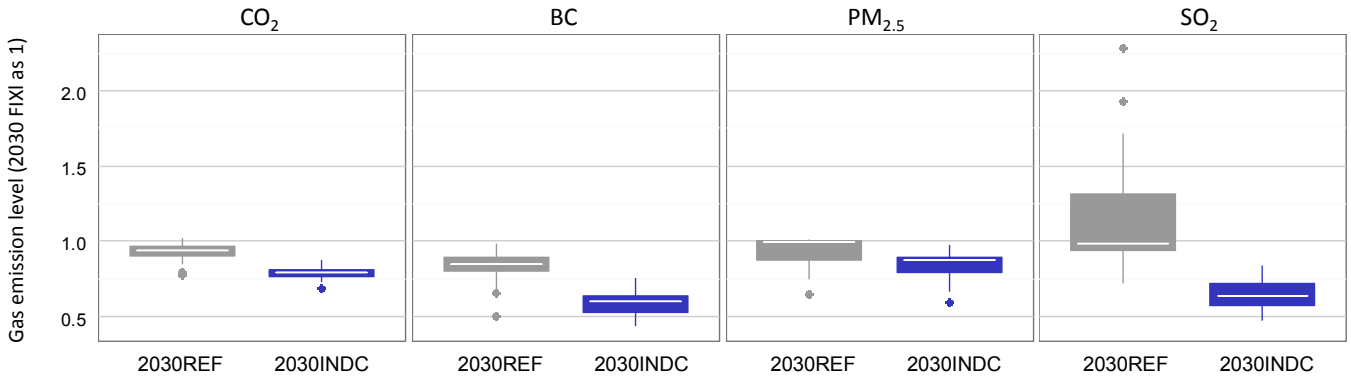

Fig. 6. Comparison of residential gas emission levels in 2030 (2030 FIX = 1).

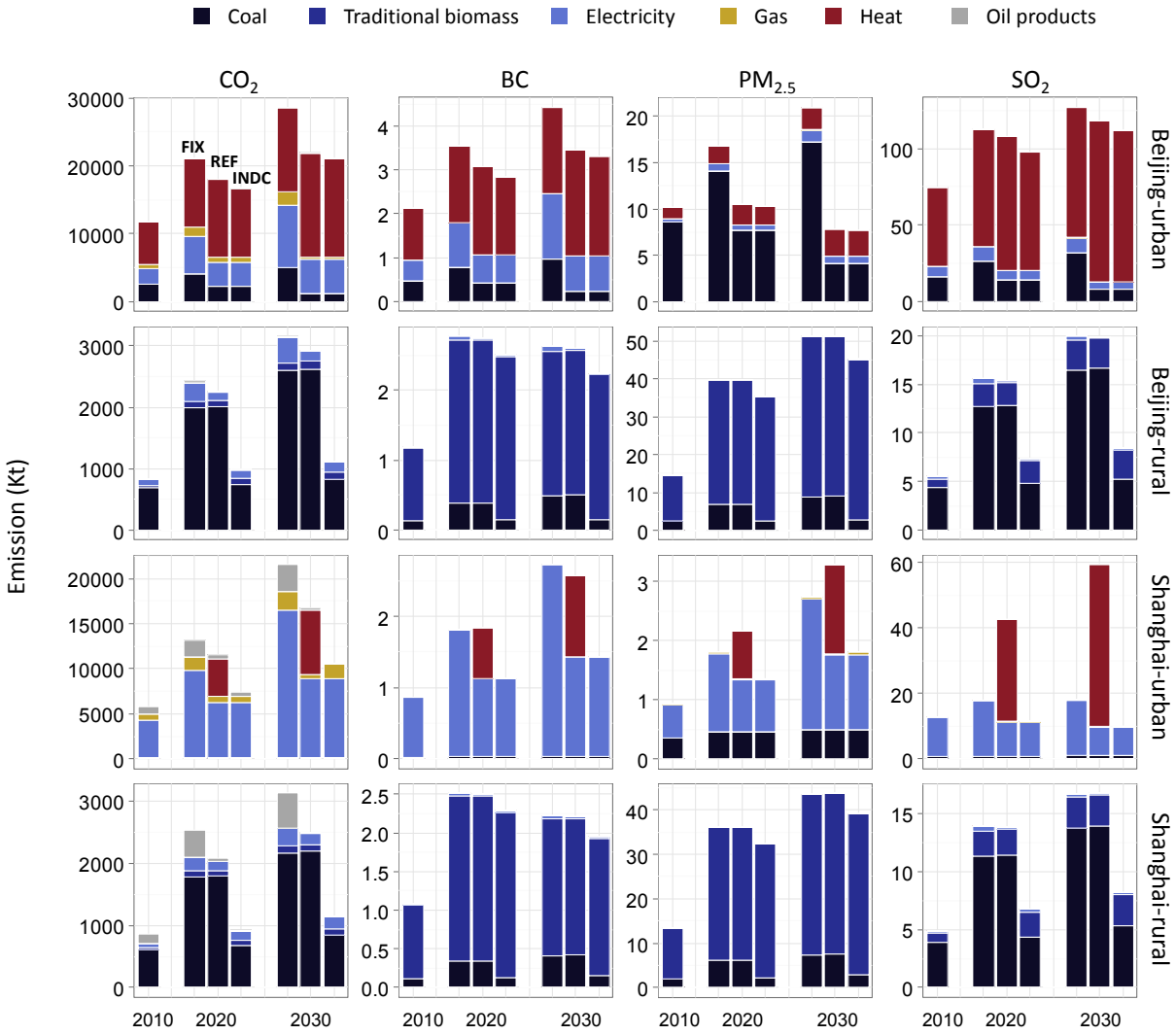

Fig. 7. Regional emissions of CO_2, BC, $PM_{2.5}$, and SO_2.

as Shanghai, also have demand for heating services during winter. Although present-day central heating is not provided in those regions, during model estimation, central heating is prepared as a future alternative. The results show that in the REF scenario central heating will be selected as a low-carbon heating technology in urban Shanghai.

3.3. Carbon price sensitivity in the residential sector

The reduction rate of CO_2 emission intensity per GDP in China's INDC targets is set in a range of 60%–65%. In the previous sections, we analyzed effects of the lower boundary (i.e. a 60% CO_2 intensity reduction) of the INDC targets to focus on discussions about the

major characteristic of emission profiles and provincial profiles. However, to understand the effects of the INDC ranges on China's provincial urban and rural areas, we also examined the range of carbon prices to realize the range of China's INDC in the residential sector. It was found that when the CO_2 emission intensity target is strengthened from 60% to 65%, total residential CO_2 emissions are reduced from 604 to 529 Mt CO_2 in 2030. Fig. 8 shows the range of CO_2 emissions in the residential sector when examining the different levels of carbon taxes from \$0 to \$100US/tCO_2 at \$10US/tCO_2 increments. We found that achieving the 60% and 65% CO_2 intensity reduction targets can be estimated in a range of around \$40 to \$60US/tCO_2. In order to characterize the upper and lower boundary of the INDC targets, we then examined emission features under a carbon tax from \$40 to \$60US in \$2US increments. There is a price sensitivity around \$54US/tCO_2 and emission features are different between the upper and lower boundary of the INDC targets.

We found that no emission reduction takes place at the carbon taxes ranging from \$0 to \$10US/tCO_2. Hence, a carbon tax of \$10US/tCO_2 is too low to incentivize the introduction of additional efficient technologies beyond what is achieved in the REF scenario, which is at \$0 US/tCO_2. There are three major decreasing trends of CO_2 emissions when imposing carbon tax between \$10 and \$70US/tCO_2. As the carbon tax rises from \$10 to \$40US/tCO_2, there is a drastic CO_2 reduction because efficient refrigerators in urban areas and efficient coal heating stoves in rural areas can be introduced. The rate of emission reduction slows down after the carbon tax reaches \$40 to \$54US/tCO_2, and carbon price sensitivity is very weak for changing CO_2 emission profiles. Thus, the lower boundary of the INDC target at a 60% CO_2 intensity reduction can be realized with carbon taxes of around \$44 to \$54US/tCO_2. However, CO_2 emission falls sharply again from \$54US/tCO_2 until the carbon tax reaches \$70US/CO_2 when gas heating devices and the most efficient coal stoves are respectively introduced in urban and rural areas. During this second sharp decrease, the 65% CO_2 intensity reduction target is realized with a carbon price of \$58US.

3.4. CO_2 abatement cost curve

Fig. 9 shows examples of abatement cost curves in the REF scenario in 2030 in four representative Chinese provinces: Beijing, Hebei, Shanghai, and Anhui. The four provinces are presented to format a matrix of different income levels and different climate zones. Overall reduction potentials in urban areas are much larger than those of rural areas due to the much larger amounts of higher service demands in urban households (see Fig. 2). Fluorescent lamps are the most cost effective option compared to other mitigation options among all sub-sectors such as heating, cooling, hot water, cooking, lighting, and other electronics, and are thus selected by all regions as the first option of cost effective technologies. The second least cost technology among all sub-sectors for all regions are energy efficient refrigerators. The reduction potential of efficient refrigerators is larger in urban areas compared to rural areas. Other technology selections differ from region to region depending on regional characteristics. Compared to the rural residential sector, the urban residential sector has more efficient technology options to achieve no-regret CO_2 emission reduction because efficient technologies are less cost competitive in rural areas. It is easier for urban households to adopt efficient technologies. Table 4 summarizes the major efficient technologies with significant reduction potentials in the REF scenario. It is important to note in Fig. 9 that no-regret CO_2 reduction potential is quite large in China's residential sector. If it is at no-regret cost, it means that itis more cost effective as an option than others, and people are likely to choose such cost-effective options. However, in line with realistic current social trends, these efficient technologies at no-regret cost are difficult to promote widely in households due to various social barriers. One of the main barriers might be the so called “split incentive” between landlords and tenants (Bird and Hernandez, 2012). In urban areas, many people live in rental apartments. In many cases, these are furnished or semi-furnished apartments. Although efficient technologies bring both financial benefits and CO_2 emission reduction (hence the no-regret reduction), usually these technologies require longer payback periods than the payback sensitivity of people's behavior. For people who only stay in an apartment for a few years or less, these tenants see no short-term benefit of investing in efficient but expensive equipment which has longer payback periods. Therefore, it is important to attract landlords as well as tenants to invest in energy efficient household technologies from the viewpoint of longer payback periods. To make improvements, government policies, such as subsidies on efficient equipment, reform of the energy billing system among landlords and tenants, and energy conservation regulation of household appliances, may be helpful in further promoting

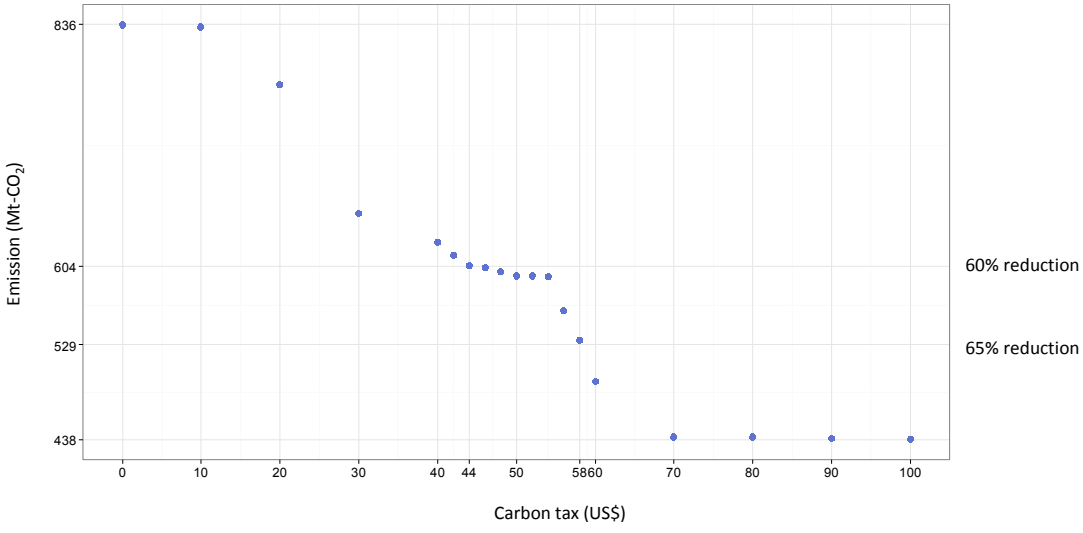

Fig. 8. Carbon price in the residential sector necessary to achieve China's INDC.

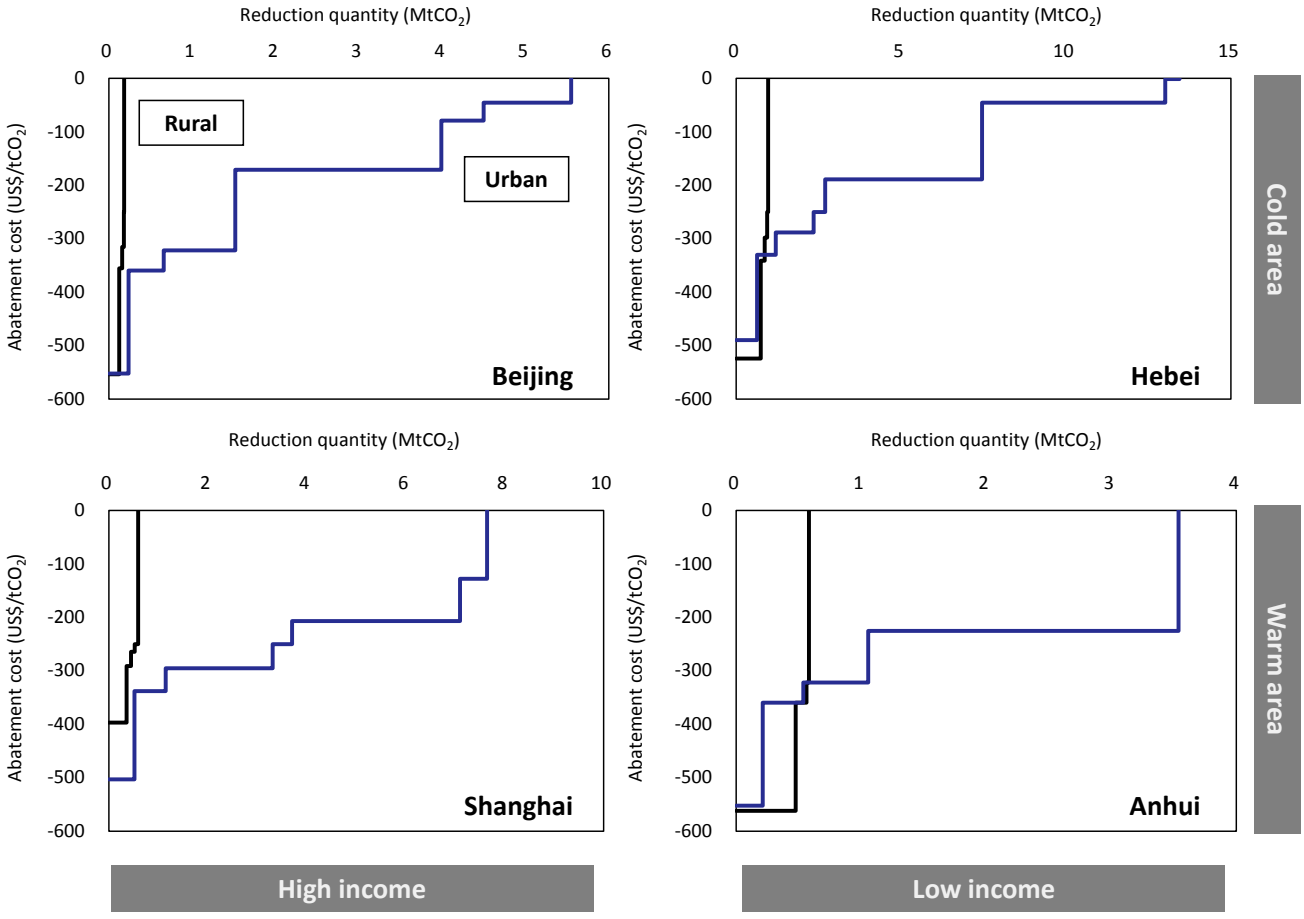

Fig. 9. Abatement cost curves in four representative Chinese regions (REF scenario).

Table 4
Major technologies with significant reduction potentials (REF scenario; U=Urban, R = Rural).

Application	Technology	Reduction potential ($MtCO_2$)							
		Beijing		Hebei		Shanghai		Anhui	
		U	R	U	R	U	R	U	R
Heating	Coal boiler (district heating, conventional)	1.05		5.55					
Cooling	Air conditioner for cooling (conventional)			0.23		0.24			
Hot water	Biomass water heater (efficient)	2.47		4.76		3.39		2.48	
Cooking	Biomass cooking range (efficient)	0.51		0.43		0.55			
Lighting	Fluorescent lamp (best available technology)	0.24	0.12	0.64	0.75	0.52	0.36	0.21	0.48
Other	Refrigerator (best available technology)	0.42	0.04	0.56	0.12	0.63	0.09	0.33	0.09
	Other equipment (efficient)	0.86	0.02	1.15	0.08	2.16	0.07	0.52	0.02
	Television (conventional)		0.00	0.13	0.02	0.16	0.07		

penetration in Chinese households.

The level of carbon taxation for achieving the lower boundary of the INDC target at a 60% CO_2 intensity reduction in 2030 is at \$44US/tCO_2 as illustrated in Fig. 8, while Fig. 10 shows the shape of abatement cost curves in the lower boundary of the INDC targets in the same four Chinese regions of Beijing, Hebei, Shanghai, and Anhui. The abatement cost curve represents mitigation costs and cumulative mitigation potentials under the \$44 US/tCO_2 carbon price. Compared to the REF scenario, the most efficient coal stove is newly selected in the rural areas of Beijing, Shanghai, and Anhui. No technology is newly selected for rural Hebei, meaning that the carbon price around \$44US/tCO_2 is not sufficiently cost sensitive to encourage the introduction of more efficient technologies than the REF level. In urban areas, technology selections are identical to the results in the REF scenario, which indicates that the abatement costs for further introducing efficient technologies in these four regions are more than \$44US. As shown in Fig. 8, the marginal cost of the upper boundary of the INDC targets is around \$58US/tCO_2. When the CO_2 emission intensity reduction target is strengthened from 60% to 65%, reduction profiles are almost the same in rural areas but urban areas are required to achieve more reduction potentials. To achieve the 65% reduction target, two efficient biomass technologies are newly selected for urban Anhui. Thus, it is important to note that to achieve the upper boundary of the INDC targets, both urban and rural areas need to make efforts for greater penetration of efficient technologies compared to the REF scenario whereas only rural areas must cover additional efforts from the REF scenario to achieve the lower boundary of the INDC targets.

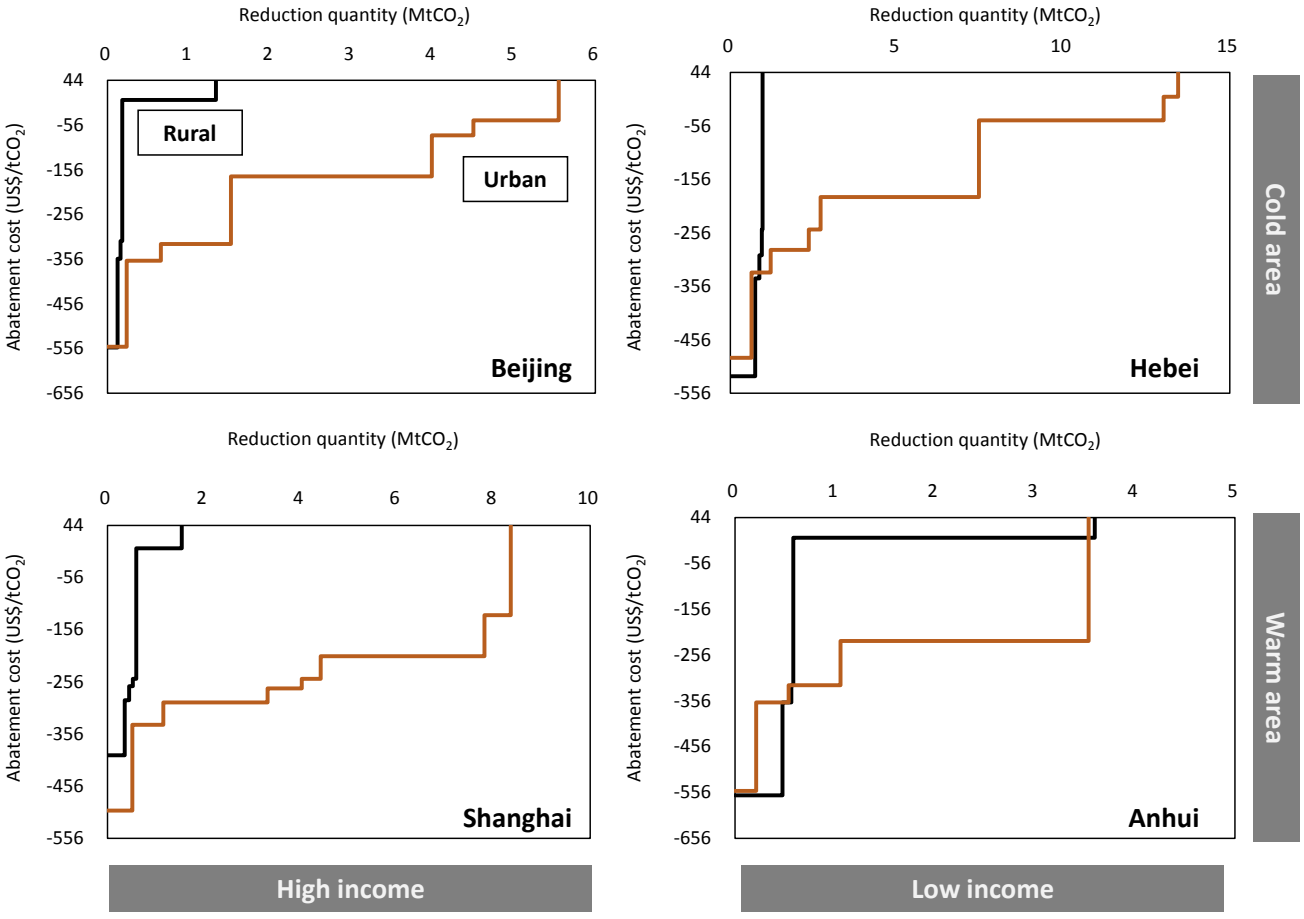

Fig. 10. Abatement cost curves in four representative Chinese regions (the lower boundary of achieving the INDC scenario).

Table 5 shows the newly selected major technologies with significant reduction potentials in both the lower and upper boundaries of the INDC scenario. One efficient technology is newly selected to achieve the lower INDC target (60% reduction) and three efficient technologies are newly selected to achieve the upper INDC target (65% reduction). Since this study is on a regional basis, the results of selecting efficient technologies is analyzed for each provincial region, and with respect to urban and rural areas. However, the cost optimization leads to preferential mitigation actions in rural areas, which is not realistic considering the inequality between urban and rural areas in their capability to pay for mitigation options. Thus, it is important to consider policy instruments, such as energy subsidies and technological supports, in the rural residential sector.

4. Conclusion

This study concentrates on the effects in the residential sector of achieving China's INDC while estimating the emission reduction potentials for CO_2 and three other air pollutants. By conducting a scenario analysis, the following four key findings are observed.

1) The implementation of efficient technologies can bring about a large amount of no-regret CO_2 reduction in the REF scenario. The emission reductions of BC, $PM_{2.5}$, and SO_2, however, are limited in the REF scenario.
2) To achieve China's INDC, additional efficient technologies need to be implemented in both rural and urban households. Achieving the mitigation targets in INDC also benefits emission reductions of BC, $PM_{2.5}$ and SO_2. Compared to the FIX scenario,

Table 5
Major technologies with large reduction potential (newly added in INDC scenario; U=Urban, R = Rural).

Application	Technology	Reduction potential ($MtCO_2$)							
		Beijing		Hebei		Shanghai		Anhui	
		U	R	U	R	U	R	U	R
INDC lower boundary (60% reduction)									
Heating	Coal stove (best available technology)		1.15				0.94		3.01
INDC upper boundary (65% reduction)									
Heating	Coal stove (best available technology)		1.15				0.94		3.01
Heating	Biomass heating stove (conventional)							0.80	
Cooking	Biomass cooking range (conventional)							0.26	

CO_2, BC, $PM_{2.5}$, and SO_2 emissions from the residential sector in the INDC scenario are respectively reduced by 38%, 21%, 16%, and 31% in 2030.

3) The reduction rates vary across provinces due to climatic variations and economic disparities. The FIX-compared reduction rate appears to be correlated with climate characteristics. Under a national carbon emission cap, warm regions contribute more to total emission reduction. CO_2 emission reduction potential in cold regions is mainly contributed to by efficient heating devices (central heating), while in warm regions reduction potential is mainly contributed to by efficient electricity devices.
4) There are three major decreasing trends of CO_2 emissions when imposing a carbon tax between \$10 and \$70US/tCO_2. The 60%–65% reduction target in China's INDC can be realized with carbon prices of \$44 to \$58US in the residential sector.
5) Analysis results of abatement cost suggest that fluorescent lamps and efficient refrigerators are two major cost competitive technologies that can be introduced in most of the provincial regions to achieve no-regret CO_2 reductions. Furthermore, in order to achieve the upper boundary of the INDC targets, both urban and rural areas need to take measures to increase the penetration of efficient technologies compared to the REF scenario.

The remaining issue of this study is to explore several aspects not well covered by our present analyses. First, due to limits in the data available on energy policies and energy prices of non-commercial biomass in rural households, we could not discuss an appropriate energy transition process for the future, thus we set the maximum share of non-commercial biomass as the same level as the base year level in future scenarios. According to the "energy ladder" theory (Hosier and Dowd, 1987; Van der Kroon et al., 2013), the household energy source switches from non-commercial energy to commercial energy when income grows. Future surveys could provide more insights into the fuel-switching dynamics in China's rural household sector. Second, our study focuses solely on the residential sector on the assumption that all 31 provinces use a national electricity grid. As such, we apply an average emission factor for electricity for all 31 provinces in order to evaluate the impact from the demand side only. Future iterations of the AIM/Enduse model will provide technical support for linking the electricity supply sector with the demand sector. The variation of electricity generation sources (e.g., the share of hydropower) across the provinces can be covered by setting regional electricity factors in order to evaluate the impact from supply.

Notes

1. In China provincial-level divisions include provinces, municipalities, autonomous regions and special administrative regions.
2. The rural areas mentioned in this study are the national administrative divisions treated as "rural areas" in the "China Statistical Yearbook" (NBSC, 2012).

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